# Community College Solar Engineering Unit

**Subject:** Optimizing energy costs using solar energy; Modelling trade-offs between different sources of power loss and electron transport on a solar cell.

**Grade Levels:** Community College (may also be appropriate for some high school classes and some university courses)

**Lessong Length:** three class sessions

**Authors:** Cody Anderson, Elizabeth Adams

This unit was designed to be used in general engineering courses in the community college setting. The unit is divided into two parts. On Day 1, students are introduced to the big picture of solar applications and they design a solar array for their home. On Days 2 and 3, students zoom in to understand how solar cell engineering tradeoffs affect solar energy applications. They learn how a solar cell works and designing a cell for optimization.

## Day 1 – Big Picture. Why solar? Design a solar array for your home.

Materials

- Copy of each students' recent power bill
- PowerPoint on Photovoltaic applications (found on the QESST Education website)
- "CAA_pvwatts_hourly" Excel spreadsheet posted to the course website or one copy printed for each student
- "CAA_pvwatts_monthly" Excel spreadsheet
- Access to a computer for each student

- Copy of the PVWatts Caltulator Assignment for each student (see document in Appendix for this lesson).
- Copy of the Utility Bill Review in-class worksheet for each student (see document in Appendix for this lesson).

Opener: Utility Bill Review

- Students partner up and compare their power bills. They discuss reasons for differences in energy use and cost.

Lecture: Photovoltaic applications (The PowerPoint for this lecture can be found on the QESST Education website)

Assignment: PVWatts_Calculator

- In-class, students complete Part 1, which is sizing a solar array for their home through the PV Watts Calculator
- As homework, students complete Part 2, which is using Excel to analyze the Monthly and Hourly outputs from the PV Watts Calculator

<u>Day 2 - PV mechanics. Details on how the solar cells work. Front grid design optimization.</u>

Materials

- Day 1 homework
- PowerPoint on PV Mechanics found on the QESST Education website
- Copies of the Front Grid assignment for each student (attached at end)
- Front_Grid_Optimization Excel spreadsheet found on the QESST Education website
- Competition_Spreadsheet Excel found on the QESST Education website

Students bring in: Day 1 homework

Opener: Review the Excel analysis

Lecture: PV_mechanics (The PowerPoint for this lecture can be found on the QESST Education website)

Assignment: Front_Grid_assignment

- In-class, students complete Part 1, where they draw their own front grid designs, partner up, compute power losses from their drawings, and compare results with each other.
- As homework, students complete Part 2, which is using Excel to inform their front grid designs and developing their most efficient design.
- Note: See the Designing a Solar Cell to Optimize Efficiency in the Outreach Activity section of this book for another description of how to enact this activity

Day 3 (only the first 20 minutes of class) – Front grid optimization and competition

Materials and Resources

- Day 2 homework
- "Competition_Spreadsheet" Excel
- Copy of the Front Grid Assignment for each student

Students bring in: Day 2 homework

Opener: Review the Excel analysis

Competition: Using the "Competition_Spreadsheet," have students share the parameters for their optimal design and see who demonstrates the smallest power loss

# In-Class Activity - Utility Bill Review

Partner up with your neighbor and review the power bills you brought in. Provide thoughtful responses to the following questions using proper grammar and complete sentences.

A) Fill in the table with data from the two bills. For the last column, compute the true cost of the energy (remove the costs of service charges and taxes)

| | | |
|---|---|---|
| Location | | |
| Date | | |
| Total Energy Use [kWh] | | |
| Total cost [$] | | |
| Average cost per kWh [$/kWh] | | |

B) What could account for the differences between the two bills? Include as many reasonable factors you can think of. Which of these factors might be most/least important?

C) Describe (in your own words) what you are paying for when you pay this bill (Power? Energy? Electricity?). How do you know?

*This assignment consists of two parts. The first will be completed in-class and the second as a homework assignment. Submit all parts together next class period.*

## Part 1: Construct a model solar array for your house

Access the National Renewable Energy Laboratory (NREL) PVWatts Calculator and use it to design a PV array for your home:

PVWatts.NREL.gov

If you have questions about what is required for the different inputs, look for the information icon. ⓘ

Record your input values here (including units). Write notes to justify your choices.

| | |
|---|---|
| Zip code | |
| Solar resource data | |
| DC System size | |
| Module type | |
| Array Type | |
| System Losses | |
| Tilt | |
| Azimuth | |
| | |
| DC to AC Ratio | |
| Inverter Efficiency | |
| Ground Coverage Ratio (for 1-axis tracking only) | |
| Initial Economics | |
| System Type | |
| Average cost of electricity from utility bill | |

## Part 2: Analyze the energy output results

Output Data Analysis

Download the output results (both Monthly and Hourly). Open these files and save them as .xlsx files.

PVWatts_Monthly.xlsx

A) Define each of the output column parameters below:

| | |
|---|---|
| AC System Output (kWh) | |
| Solar Radiation (kWh/m2/day) | |
| Plane of Array Irradiance (W/m2) | |
| DC Array Output (kWh) | |
| Value ($) | |

B) Identify the month of maximum AC system output and plane of array irradiance. ______________________

C) Identify the month of minimum AC system output and plane of array irradiance. ______________________

D) Plot AC system output on the primary y-axis, plane of array irradiance on the secondary y-axis, and months on the x-axis. Label the axes in your own words (e.g. translate "Plane of array irradiance" to something more understandable)

E) In a text box near the plot, type up a short paragraph (4-6 sentences) caption for your plot. The caption must clearly describe the "story" your plot is telling.

F) Print out a page showing the plot and caption

PVWatts_Hourly.xlsx

A) Define the output column parameters listed below:

| | |
|---|---|
| Beam Irradiance (W/m2) | |
| Diffuse Irradiance (W/m2) | |
| Plane of Array Irradiance (W/m2) | |
| Ambient Temperature (Celsius) | |
| Cell Temperature (Celsius) | |

B) Use Excel functions to find the maximum ambient temperature occurring during the year. Fill in the results below.

| Max Ambient Temp. | Month | Day | Hour |
|---|---|---|---|
| | | | |

Does the timing of the maximum ambient temperature correspond with the month your system generated the most electricity? Below, explain why the timing of these two is close (or far) apart:

____________________________________________________________

____________________________________________________________

C) Create TWO scatter plots with AC system output on the primary y-axis and hours on the x-axis:

- For the month you identified producing the maximum AC system output
- For the month you identified producing the minimum AC system output.
- Set the y-axis limits to be the same on each plot. Include proper titles and axes labels

D) In a text box near the two plots, type up a short paragraph (5-7 sentences) caption. The caption must summarize the story that each plot is telling and compare results between the two.

E) Print out a page showing the caption and two plots

To turn in:

This written assignment (all three sheets) with completed definitions and all questions answered

Printed page showing caption and plot for the Monthly data

Printed page showing caption and plots for the Hourly data

# Front Grid Optimization

In this assignment, our goal is to optimize the front grid design of a solar cell to minimize power loss. We will do this by drawing our own custom designs and estimating power loss, then using a spreadsheet to develop a better design.

The power loss [%] associated with the front panel design of a solar cell can be mathematically modeled as shown below. Note that this excludes power loss due to busbar resistance (negligible) and due to contact resistance (cannot be modeled well). These equations assume equal finger spacing throughout cell.

$$P_{loss} = P_{loss,emitter} + Pl_{oss,fingers} + P_{loss,shading}$$

$$P_{loss,emitter} = (S_f^2\ J_{mp}\ p) / (12\ V_{mp})$$

$$P_{loss,finger} = (L_f^2\ S_f\ J_{mp}\ \rho) / (3\ w_f\ d_f\ V_{mp})$$

$$P_{loss,shading} = A_{shaded}/A_{cell}$$

Definitions of parameters

$S_f$ = finger spacing [mm]

L = finger length [mm]

$J_{mp}$ = current density at max power

$V_{mp}$ = voltage at max power

ρ = metal conductivity

p = emitter sheet resistivity

$d_f$ = depth of finger

$w_f$ = width of finger

$A_{cell}$ = surface area of cell

$A_{shaded}$ = shaded surface area

For our solar cell design, we are able to adjust a handful of the parameters:

- Finger spacing ($S_f$) can vary to any width you select. This parameter plays into all three of the power loss terms.
- Finger Width ($w_f$) must be at least 50 µm due to manufacturing constraints.
- Busbar spacing/finger length (L) can be any size you choose. Busbars should be spaced evenly and the finger length sized accordingly.

For the rest of the parameters, we will use typical values for a solar cell:

- $J_{mp}$ = 0.35 mA/mm2
- $V_{mp}$ = 0.5 V
- ρ = 3x10-5 Ω·mm
- p = 60 Ω
- $d_f$ = 0.02 mm
- Busbar width = 2 mm
- Acell for the given cell is 150mm x 150mm, minus the corner cutouts
- Ashaded can be estimated as $A_{shaded} = A_{busbar} + w_f / S_f\ (A_{cell} - A_{busbar})$

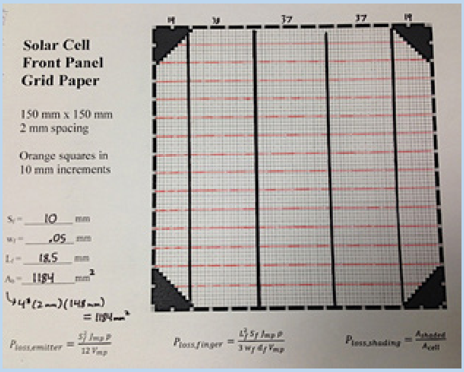
## Part 1: In-class assignment

1) Form a team of two
2) Discuss with your partner the impacts of each of the adjustable parameters (e.g. What happens if we space the fingers further apart? How does it impact each of the three power loss terms? How does it impact the total power loss?).
3) Each person take a copy of the front panel grid paper, ruler, red pen, and black pen. Choose the number of busbars that you will want to draw (between 1 and 8) (pick a number different from your partner)
4) Follow the instructions on the following page to draw your first front grid design
5) After drawing your design, compute power loss using the given equations. Verify that your units work out (note: 1 V = 1 A·Ω). Check your partner's work.
6) Discuss with your partner and write short answers the following questions. Take special note of the tradeoffs that exist:
    a. What are the impacts of increasing finger spacing?
    b. What are the impacts of increasing finger width?
    c. What are the impacts of having more busbars?
    d. To which parameter(s) are your power losses most sensitive? Least sensitive?
    e. What were the power losses for each of your designs? Why do you believe one performed better than the other?
7) Submit your answers with both teammates' names at the top.

## Steps for drawing a front grid design

1) Acquire the following:

- Copy of the front panel grid paper
- Straightedge
- Black marker
- Red pen




2) Decide how many busbars you'd like to use (between 1 and 8). All the busbars we will draw should run vertically and be evenly spaced. The example to the right was done using four busbars (black lines).

3) Compute the spacing of the busbars. Use the following table to help you (if you choose a different # of busbars, follow the pattern shown). The busbar spacing is based on a 150mm-wide solar cell and rounded to the nearest mm.

| # busbars | 1 | 2 | 3 | 8 |
|---|---|---|---|---|
| Fraction of solar cell reached by each side of the busbar | 1/2 | 1/4 | 1/6 | 1/16 |
| Busbar spacing from left edge of cell | 75 mm | 38 mm | 25 mm | 9 mm |
| Busbar spacing from each other | -- | 76 mm | 50 mm | 18 mm |

4) Draw your busbars in black marker. The width of each busbar is set at 2 mm, which is one cell's width on the grid paper.
5) Choose a finger spacing ($S_f$) between 1 mm and 10 mm. Draw your fingers in red pen.
6) Don't worry about how wide the red pen lines appear on your drawing. You can simply declare any finger width ($w_f$) you'd like ( ≥0.05 mm ).
7) Next to your design, write down the values for $S_f$, $w_f$ , $L_f$, and $A_{busbar}$.
8) You have already chosen $S_f$ and $w_f$
9) Lf is essentially the same as the busbar spacing from the left edge of cell (minus half the width of the busbar)
10) $A_{busbar}$ can be computed by realizing that all the busbars are rectangles; add all the areas of the individual busbars together.

## Part 2: Homework

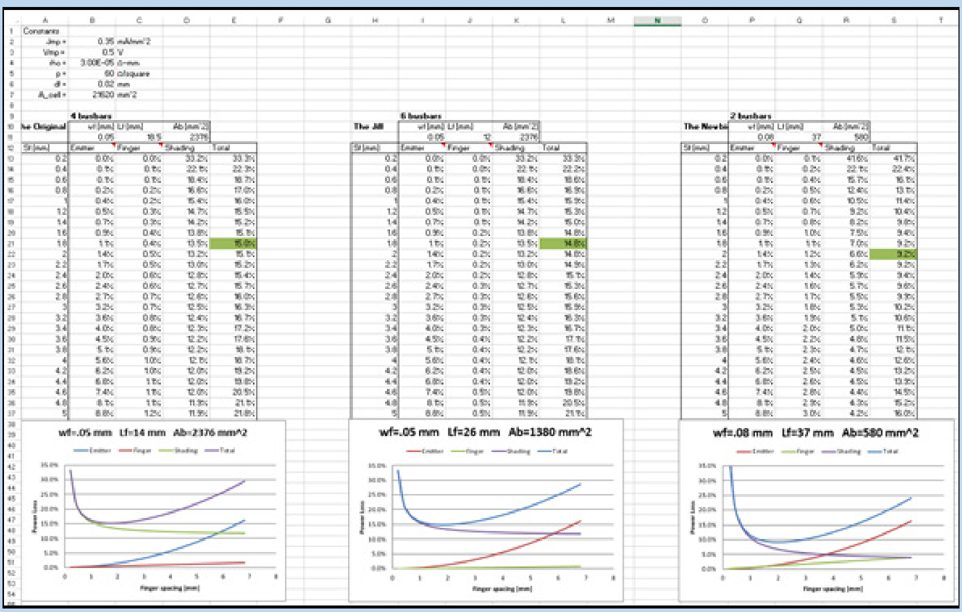
Now that we have a feel for the grid design and the power loss equations, we will take a more systematic approach for optimizing the design. There will be a competition to see who creates the most efficient design. For you to work on individually:

1) Create an Excel worksheet. To the right is a zoomed-in view of the first table. Below is a broad view of what the overall spreadsheet will look like.

- At the top of the sheet, define the parameters that won't change
- Within the computation table, declare the adjustable parameters (finger width, finger length, busbar area). Let finger spacing be the independent variable, as shown.

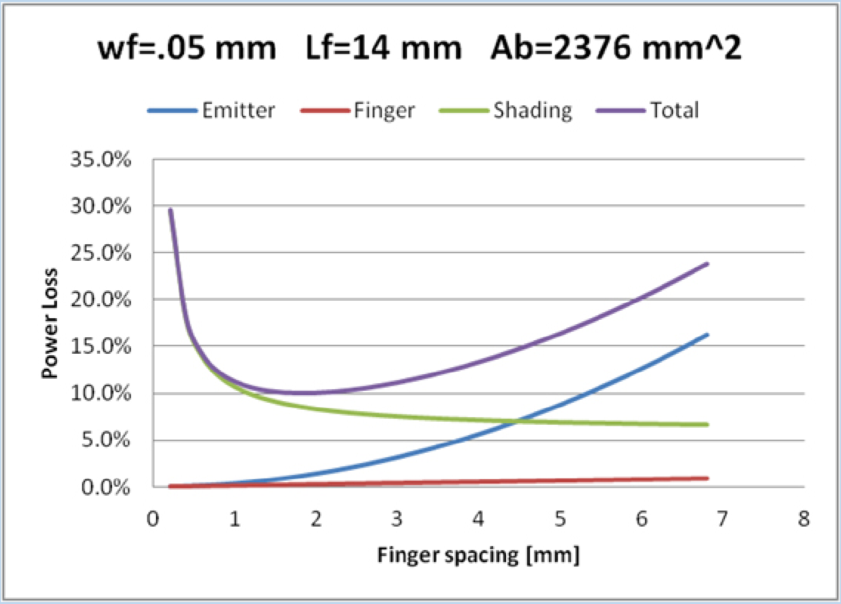
| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Constants | | | | |
| 2 | Jmp = | 0.35 | mA/mm^2 | | |
| 3 | Vmp = | 0.5 | V | | |
| 4 | rho = | 3.00E-05 | Ω-mm | | |
| 5 | p = | 60 | Ω/square | | |
| 6 | df = | 0.02 | mm | | |
| 7 | A_cell = | 21620 | mm^2 | | |
| 8 | | | | | |
| 9 | | 4 busbars | | | |
| 10 | **The Original** | wf [mm] | Lf [mm] | Ab [mm^2] | |
| 11 | | 0.05 | 18.5 | 2376 | |
| 12 | Sf [mm] | Emitter | Finger | Shading | Total |
| 13 | 0.2 | 0.0% | 0.0% | 33.2% | 33.3% |
| 14 | 0.4 | 0.1% | 0.1% | 22.1% | 22.3% |
| 15 | 0.6 | 0.1% | 0.1% | 18.4% | 18.7% |

- With the parameters set, compute all of the power loss terms. Use appropriate cell references so you can easily copy & paste and also adjust the parameters easily.
- Be careful with the units and format power losses as a %



2) Create plots of $P_{loss}$ vs. $S_f$.

- See the plot below as an example. Notice how $S_f$ is the independent variable. This allows us to see what the optimal finger spacing is for a given set of values for $w_f$, $L_f$, and $A_b$.
- Create at least three of these plots (use different sets of parameter values for each).




3) Competition.

- Based on your analysis spreadsheet, settle on what you believe is the optimal front grid design. Draw this design on a new grid paper. On the paper, list your values for $w_f$, $L_f$, $A_b$, and $S_f$.
- At the start of next class, we will compare everyone's results and see who has the most efficient design.

Submissions. Submit the following two items:

1) On the course website, upload your completed spreadsheet (with 3+ plots showing)
2) On paper, submit your hand-drawn optimal front grid (with parameters listed)

# Solar Cell Front Panel Grid Paper

150 mm x 150 mm

2 mm spacing

Orange squares in

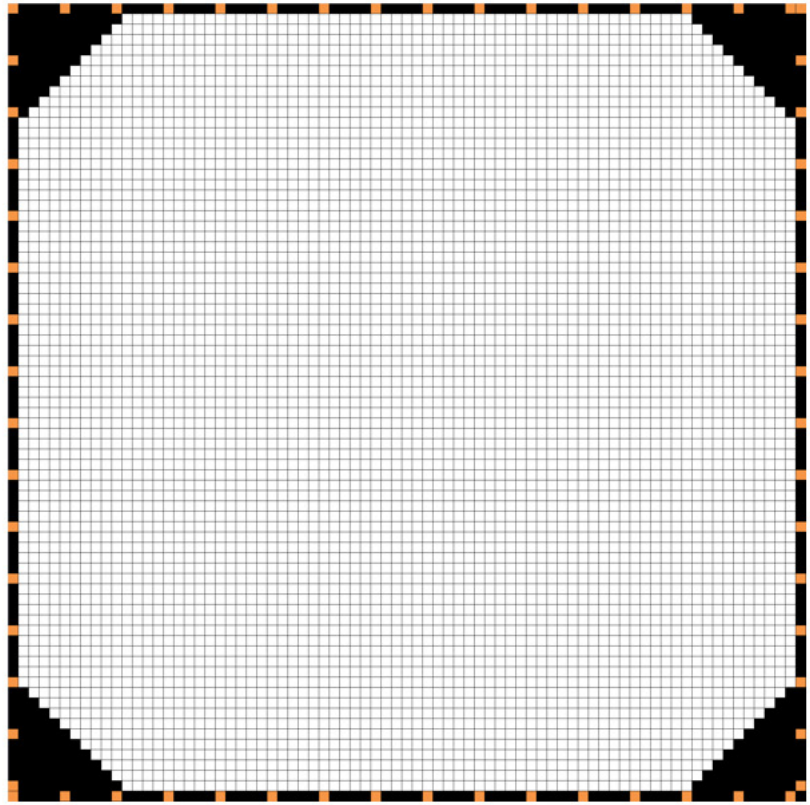
10 mm increments

$S_f$ = ____________ mm

$w_f$ = ____________ mm

$L_f$ = ____________ mm

$A_b$ = ____________ $mm^2$



$$P_{loss,emitter} = \frac{S_f^2 \, J_{mp} \, p}{12 \, V_{mp}} \qquad P_{loss,finger} = \frac{L_f^2 \, S_f \, J_{mp} \, \rho}{3 \, w_f \, d_f \, V_{mp}} \qquad P_{loss,shading} = \frac{A_{shaded}}{A_{cell}}$$